Interim Progress Report submitted to NOAA's Human Dimensions of Global Change Research (HDGCR) Program

Project Title
Sensitivity of Boulder Colorado's Water Supply to Climate Change

Investigators, including Full Contact Information

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I. Preliminary Materials

A. Project abstract

Few local governments in areas that are vulnerable to climate change have conducted an in-depth analysis of how they could be affected by climate change and how they might have to change their operations or infrastructure as a result.

The City of Boulder, Colorado, recently analyzed how its water supply system could be affected by a repeat of drought events from the last 300 years of climate, as reconstructed through tree ring analysis. That study included some sensitivity analyses on climate change.

This project will study the potential effects of climate change in combination with a repeat of long-term climate variability. It will analyze how snowpack accumulation and runoff patterns could be affected by changes in climate that could occur by 2030. It will then analyze how much of a reduction in runoff would result in missing water supply reliability targets and, based on the analysis of output from many climate change models, the rough likelihood of such an event. Finally, it will analyze two relatively extreme wet and dry climate change scenarios to see how the water supply system could be affected.

B. Objective of research project

This project addresses how water supply planners can account for changes in variability and mean climate in their long-term planning. Typically, water planning is done by examining climate records, and using these data to estimate the intensity and frequency of extreme events and to plan for the most extreme events on record. However, the analysis of climate preceding the observed record, reconstructed from tree rings and other sources, often shows that extreme events in the past were more severe than what is in the much shorter record of observations. In addition, climate change resulting from increased greenhouse gas concentrations will raise average temperatures and increase the intensity of the hydrologic cycle. This means that extreme events in the future could be more severe.

C. Approach

In this study we will attempt to integrate the analysis of climate variability and climate change with an analysis of Boulder’s coping capacity. The work will be carried out in four tasks:

1. *Analyze effects of temperature on snowpack and demand.* Stratus Consulting will estimate changes in snowpack and seasonality of runoff from incremental increases in temperature (e.g., +1°C, +2°C, +3°C). Based on the analysis of the MAGICC/SCENGEN model developed by Dr. Tom Wigley of the National Center for Atmospheric Research, a 1.5°C warming has the highest probability for Colorado by 2030. Hydrosphere Inc. will use the snowpack and runoff results

from Stratus Consulting as inputs to the City of Boulder's Boulder Creek Watershed Model to examine the effects of a 1.5°C warming on supply, demand, and reliability. The analysis will be done by combining changes in runoff with a reconstruction of the 1566-2002 streamflow in middle Boulder Creek. We have applied a bootstrapping approach to match reconstructed streamflow in years prior to climate observations with years during the period of climate observation. This yields a temperature and precipitation data set consistent with the reconstructed streamflow data set. This approach effectively includes long-term variability and combines it with climate change.

Stratus Consulting will use the Snowmelt Runoff Model (SRM), which estimates the size of snowpack and timing of snowmelt, and WATBAL, a water balance model, to estimate runoff into the creeks feeding Boulder's water supply. The analysis will be conducted for the Front Range. Since there is a high correlation between runoff in the Front Range and runoff in the Upper Colorado River, we will use the changes in runoff in the Front Range to represent changes in the Upper Colorado River runoff. This is important because Boulder draws some of its water supplies from the Colorado River.

2. *Determine coping thresholds*. Hydrosphere Inc. will use the Boulder Watershed Model, which simulates all significant aspects of hydrology, water rights, water storage, and diversion facilities, as well as water uses and return flows in the Boulder Creek basin, to examine Boulder's ability to meet water demands under climate change. To determine the threshold for acceptable reductions, Hydrosphere Inc. will examine 5%, 10%, and 15% reductions in runoff imposed on the 1566-2002 reconstructed runoff record. City of Boulder staff will analyze the results to determine what level of long-term reduction in supply would exceed the city's coping capacity, which will be considered the threshold coping capacity for the City of Boulder.

3. *Examine the likelihood of exceeding the coping capacity*. Stratus Consulting will work with Dr. Wigley to use the results of MAGICC/SCENGEN to examine the likelihood of exceeding the coping capacity by 2030 and 2070. MAGICC results will be used to develop a probability density function of changes in global mean temperature for 2030 and 2070 (the years are approximations and indicative of decadal climate changes). SCENGEN allows for comparison of regional patterns of temperature and precipitation changes across 17 general circulation models (GCMs). This output indicates what magnitudes and ranges of regional change in temperature and precipitation are possible. Using the runoff tables developed in Task 1, we will determine what increases in temperature and changes in precipitation could result in runoff reductions that would exceed the coping capacity for Boulder. We will then look at the distribution of GCM output and determine the proportion of GCMs that would result in exceedences. This will not be a probability analysis (GCM output cannot be interpreted as random independent outcomes), but will give some insight into the rough likelihoods of reductions in supply severe enough to exceed Boulder's coping capacity. We will

also use the results of the Statistical Downscaling Model applied to the United Kingdom Hadley general circulation model (HadCM3).

4. *Examine driest and wettest GCMs*. We will use the output of the driest and wettest GCMs (i.e., the combination of temperature increase and precipitation decrease from individual GCMs that result in the greatest increase or decrease in runoff) to estimate changes in supply and demand. Stratus Consulting will estimate changes in runoff and demand, and Hydrosphere will use these results to examine implications for Boulder's water management. The results will interpreted by city staff.

D. Description of any matching funds used for this project

The City of Boulder is providing staff time to participate in meetings and analyze results.

II. Interactions

A. Description of interactions with decision-makers who were either impacted or consulted as part of the study; include a list of the decision-makers and the nature of the interaction; be explicit about collaborating local institutions

Carol Ellinghouse is the Coordinator of Water Resources in the City of Boulder's Utility Division. She is representing the City on the project. Lee Rozaklis, a subcontractor to the project, runs Boulder's water management model. Both are participating in the project and are being consulted about all major decisions.

B. Description of interactions with climate forecasting community [i.e., coordination with NOAA climate forecasting divisions, the International Research Institute for climate prediction (IRI), regional or local climate forecasting entities, etc.]

We are coordinating closely with Dr. Connie Woodhouse of NOAA, who provided a 437-year reconstruction of streamflow on Middle Boulder Creek. We are consulting with Dr. Woodhouse on how to use that record and combine it with climate change scenarios. We are also working with Dr. Tom Wigley, a consultant to the project, on the application of climate change models; and consulting with Dr. Klaus Wolter of NOAA, on the use of observed climate data. We have also consulted with Dr. Rajagopalan Balaji of the University of Colorado on techniques for selecting analog years in the observed climate record to represent the period of paleoclimatic reconstruction.

C. Coordination with other projects of the NOAA Climate and Societal Interactions Division (i.e., other HDGCR, Research Applications, or Regional Integrated Sciences and Assessments projects)

We are coordinating with Brad Udall, who coordinates the Western Water Assessment at the University of Colorado.

III. Accomplishments

A. Brief discussion of research tasks accomplished. Include a discussion of data collected, models developed or augmented, fieldwork undertaken

We have built a watershed model for Boulder Creek that is based on WATBAL,[1] but also draws on the Snowmelt Runoff Model.[2] The model was calibrated to the Niwot Ridge, Long-Term Ecological Research (LTER) C-1 climate station in the upper part of the watershed. Three versions of the runoff model were developed with separate versions for dry years, middle years, and wet years. This captured extreme wet and dry years in the record particularly well.

One important challenge for this study was to derive temperatures and precipitation consistent with the paleoclimatic record. This was needed so that changes in temperature and precipitation could be combined with the observed record to yield climate change scenarios, which also incorporate paleoclimate variability. Dr. Strzepek, with assistance from Dr. Balaji at the University of Colorado, applied a “nearest neighbor” approach. This re-sampling technique selects annual streamflow values from the observed record to find years that most resemble annual streamflow in the paleo-record. The corresponding annual temperatures and precipitation from the observed record (selected using the nearest neighbors technique) can be combined to replicate the paleoclimate. The simulated paleoclimate can then be combined with GCM output. The nearest neighbor approach contains a random element in the selection of data from the observed record, which facilitates the creation of multiple realizations.

We have evaluated the Boulder Watershed Model under several climate change scenarios developed as combinations of

- 4 different models which can be described as “wet” (CCMAt63), “dry” (GFDL0 and GISS.EH), and “middle(GFDL1), as well as an average across all models
- 3 different emissions scenarios (developed by the Intergovernmental Panel on Climate Change in the Special Report on Emissions Scenarios) which each have different assumptions about population growth, economic development and energy usage (A1B, B1, and A2)
- 2 different future time periods (2030 and 2070).

In November 2007 we presented our findings to date to the Boulder Water Resources Advisory Board and were met with poignant questions and positive feedback. Following the meeting and review of the scenarios, we decided to analyze an additional scenario which reduces winter and spring precipitation.

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1. Yates, D. 1996. WATBAL: An integrated water balance model for climate impact assessment of river basin runoff. *Water Resources Development* 12:121-139.

2. Martinec, J., A. Rango, and R. Roberts. 1994. *The Snowmelt Runoff Model (SRM) User’s Manual*, M.F. Baumgartner (ed.). Geographica Bernensia, Department of Geography, University of Berne, Switzerland.

With the support of the Western Water Assessment, we will hold a one-day workshop in early 2008 to present the findings of this project. The workshop will be catered to water managers in the Front Range.

We will prepare a final report in early 2008.

B. Summary of any preliminary findings (i.e., how this research advances our scientific understanding)

Preliminary analysis of the climate change scenarios show that all scenarios project higher temperatures for the region. The models differ on precipitation; some project increased precipitation, while others project reduced precipitation. The models tend to project increased precipitation in the winter and decreased precipitation in the summer.

An analysis of the paleoclimate reconstruction of streamflow in Boulder Creek shows an average annual flow similar to that in the observed record, but has greater variability. In particular, the paleoclimate record contains longer sustained droughts (defined as successive years with annual precipitation below long-term average) than in the observed record. In addition, the lowest annual streamflow is in the paleo-record, prior to the observed record.

The calibrated model was run with incremental scenarios (e.g., 1.5, 3, and 4.5^{o}C temperature increases, +/- 10 and 20% changes in precipitation) as well as several GCM scenarios [e.g., three emissions scenarios, A1B, A2, and B1 for each of four models, (a relatively "wet" model, relatively "dry," a model that fell in the middle, and the average of all models) for both the 2030 and 2070 time periods]. Annual runoff shows very low sensitivity to temperature but greater sensitivity to changes in precipitation. The timing of snowmelt is very sensitive to runoff. A 3^{o}C warming shifts peak snowmelt from June to May, increases runoff in the spring and in the winter months, and decreases runoff in the summer and early fall. Many of the GCMs project warmer and drier summers, which could substantially increase demands for irrigation and municipal watering uses. The drier GCMs project a decrease in annual streamflow in Boulder Creek while the wetter GCMs project increases in annual streamflow.

Hydrosphere ran almost all of the climate change scenarios (that had been applied to the paleoclimate reconstruction of streamflow) through the Boulder Watershed Model (the GISS.EH model runs are still outstanding). The results were mixed. The results of the "wet" model showed, not surprisingly, that Boulder's water supply would not be negatively impacted if precipitation were to increase in the future. The middle model (GFDL1) yields a slight reduction in supplies, but not serious reduction. Results indicate that Boulder would experience the greatest number of years with reduced deliveries under conditions of the "dry" model (GFDL0), particularly for emissions scenarios A1B and A2. The water supply shortfall would be great in 2070 as opposed to 2030. In summary, of the 16 climate change scenarios (combinations of models, emissions scenarios and future years), 6 did not meet Boulder's 1 in 20 year reliability criterion, and 1 of the scenarios (GFDL0, A2, 2070) did not even meet Boulder's 1 in 1,000 year criterion.

C. List of any papers and presentations arising from this project thus far; please send reprints of journal articles as they appear in the literature

J.B. Smith, K.C. Hallett, J. Henderson, and K.M. Strzepek. 2007. Expanding the tool kit for water management in an uncertain climate. (). *Southwest Hydrology* January/February, pp. 24-25.

D. Discussion of any significant deviations from proposed work plan (e.g., delayed fieldwork due to late arrival of funds).

We have decided to use the model WATBAL to estimate runoff. It is simpler and easier to apply than the PRSM model we originally planned to use.

IV. Relevance to the Field of Human-Environment Interactions

A. Describe how the results of your project are furthering the field of understanding and analyzing the use of climate information in decision-making

We are developing a technique that can combine historic climate variability and future climate change (i.e., climate change imposed on top of increased variability) to help decision-makers adapt to resulting outcomes.

B. Where appropriate, describe how this research builds on any previously funded HDGEC research (i.e., through NSF, EPA, NASA, DOE, NGOs, etc.)

N/A

C. How is your project explicitly contributing to the following areas of study?

1. **Adaptation to long-term climate change**
   This project is addressing long-term adaptation to climate change by examining scenarios of increases in temperature and changes in precipitation. It is intended to inform stakeholders about the potential need for adaptation.

2. **Natural hazards mitigation**
   We will examine potential vulnerability to sustained drought by incorporating the paleoclimatic record on drought and adding climate change on top of natural variability.

3. **Institutional dimensions of global change**
   We are working with the City of Boulder on incorporating consideration of climate change in its long-term planning.

4. **Economic value of climate forecasts**

We will not be explicitly addressing the economic value of climate change forecasts.

5. **Developing tools for decision-makers and end-users**
   We are using probability density functions from NCAR on regional changes in climate to help select GCMs to reflect a wide range of model output. We are also developing a technique to convert streamflow reconstructions into analog temperature and precipitation records.

6. **Sustainability of vulnerable areas and/or people**
   We are examining the long-term sustainability of Boulder's water supply.

7. **Matching new scientific information with local/indigenous knowledge**
   We are working closely with decision-makers on making climate change and variability information relevant to their needs.

8. **The role of public policy in the use of climate information**
   We are working with staff involved in the City of Boulder's planning process to incorporate information on climate variability and change.

9. **Socioeconomic impacts of decadal climate variability**
   The analysis is using the paleoclimatic record to incorporate climate variability in planning, and we are imposing a long-term change in climate on top of that record. The City of Boulder will consider the impacts of changes in climate variability as expressed in the paleoclimate reconstruction.

10. **Other (e.g., gender issues, ways of communicating uncertain information)**
    N/A

V. Graphics

N/A